650 MHz Beta=0.9 Cryomodules Requirements Document

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Revision History

Revision	Date	Section No.	Revision Description
Draft 1	2/4/2011	All	Initial Draft
Draft 2	3/9/2011	All	Second Draft
Draft 3	3/31/2011	All	Third draft incorporating comments from various reviewers, additional information, and other revisions
Draft 4	5/1/2011	All	Fourth draft incorporating new information during and subsequent to the Project X collaboration meeting

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SCOPE

Cryomodules containing 650 MHz, beta = 0.9 dressed cavities and associated components (input couplers, instrumentation, etc.) shall be designed, fabricated, and tested for Project X. This document defines the cryomodule requirements.

1. **Introduction.** Project X is a multi-MW proton accelerator facility based on an H^- linear accelerator using superconducting RF technology. [1] The Project X 3 GeV CW linac employs 650 MHz cavities[2] to accelerate 1mA of average beam current of H- in the energy range 160 – 3000 GeV. We describe the requirements of the 650 MHz beta = 0.9 cryomodules (see Figure 1). The requirements may be summarized as follows:
   1.1 The baseline design concept includes cryomodules closed at each end, individual insulating vacuums, with warm beam pipe and magnets in between cryomodules such that individual cryomodules can be warmed up and removed while adjacent cryomodules are cold.
   1.2 Provide the required insulating and beam vacuum reliably
   1.3 Minimize cavity vibration and coupling of external sources to cavities
   1.4 Provide good cavity alignment (<0.5 mm)
   1.5 Allow removal of up to 250 W at 2 K per cryomodule
   1.6 Protect the helium and vacuum spaces including the RF cavity from exceeding allowable pressures.
   1.7 Intercept significant heat loads at intermediate temperatures above 2.0 K to the extent possible in full CW operation
   1.8 Provide high reliability in all aspects of the cryomodule (vacuum, alignment stability, mechanics, instrumentation) including after thermal cycles
   1.9 Provide excellent magnetic shielding for high Q0
   1.10 Minimize cost (construction and operational)

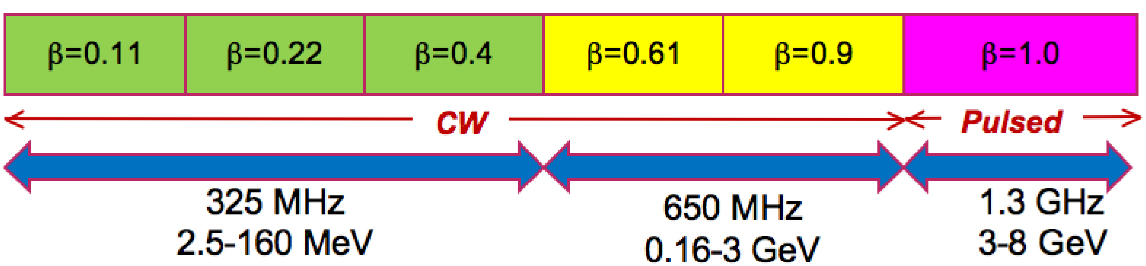

Figure 1. Project X incorporates six types of cryomodules, shown in this map. This specification document describes the requirements for 650 MHz, beta = 0.9 cryomodules.

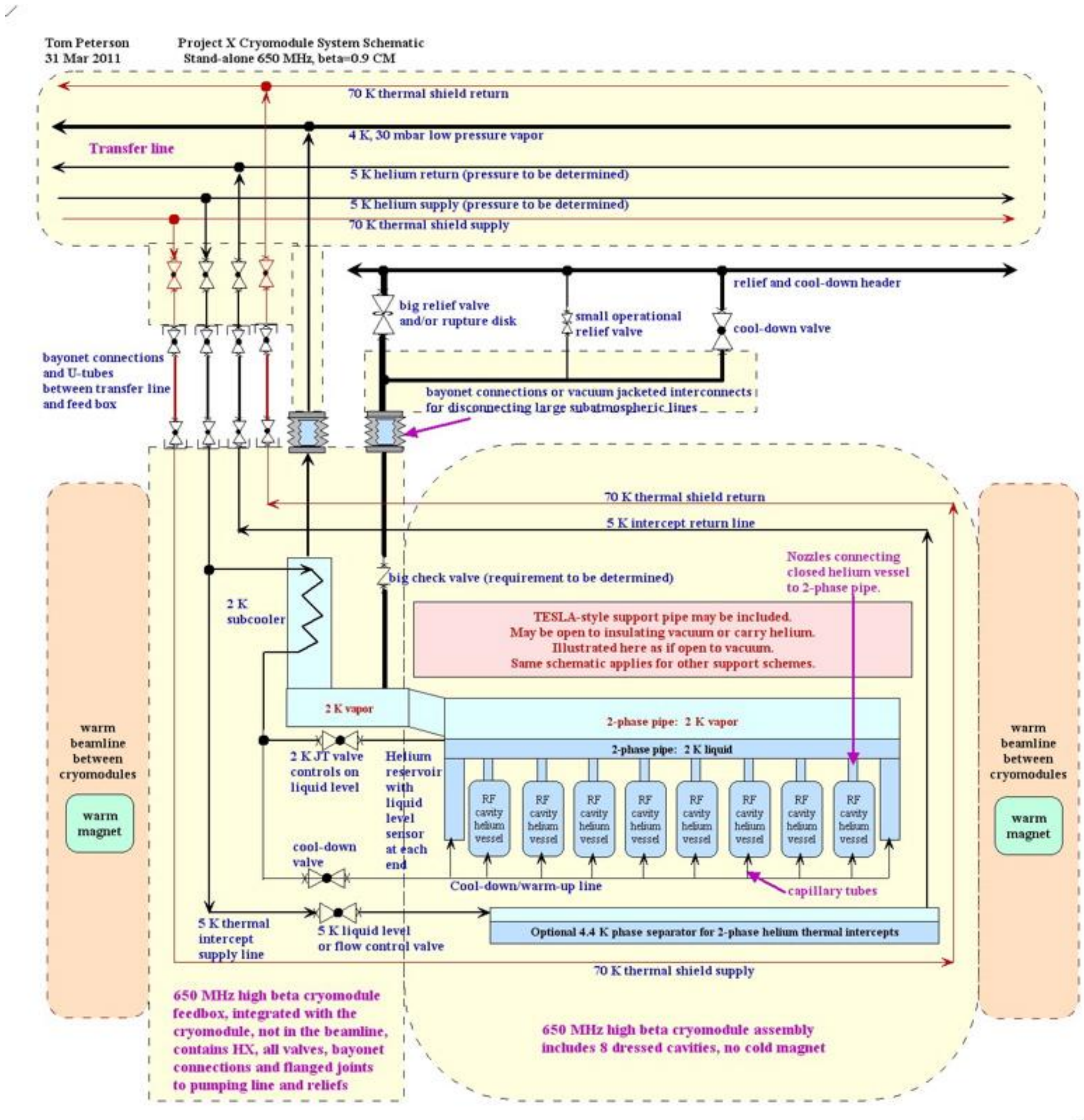

Figure 2. 650 MHz beta = 0.9 cryomodule schematic

2. Cryomodule mechanical design

2.1 Cryomodule major components. The cryomodule consists of the subassemblies and components which are integrated into one vacuum jacketed vessel. These include:

- 2.1.1 Eight (8) dressed RF cavities [1,2]
- 2.1.2 Eight RF power input couplers
- 2.1.3 One intermediate temperature thermal shield
- 2.1.4 Cryogenic piping
- 2.1.5 Cryogenic valves
    - 2.1.5.1 2.0 K liquid level control valve

- 2.1.5.2 Cool-down/warm-up valve
- 2.1.5.3 5 K thermal intercept flow control valve
- 2.1.6 Pipe and cavity support structure
- 2.1.7 Vacuum vessel
- 2.1.8 Instrumentation
- 2.1.9 Heat exchanger for 4.5 K to 2.2 K precooling of the liquid supply flow
- 2.1.10 Safety relief valves
- 2.1.11 Bayonets for helium supply and return

2.2 Major interfaces from the cryomodule to other linac components

- 2.2.1 Bayonet connections for helium supply and return
- 2.2.2 Vacuum vessel support structure
- 2.2.3 Beam tube connections at the cryomodule ends
- 2.2.4 RF waveguide to input couplers
- 2.2.5 Instrumentation connectors on the vacuum shell
- 2.2.6 Alignment fiducials on the vacuum shell with reference to cavity positions.

2.3 Cryomodule linac lattice dimensions and spacing [3] are shown in Fig 3.

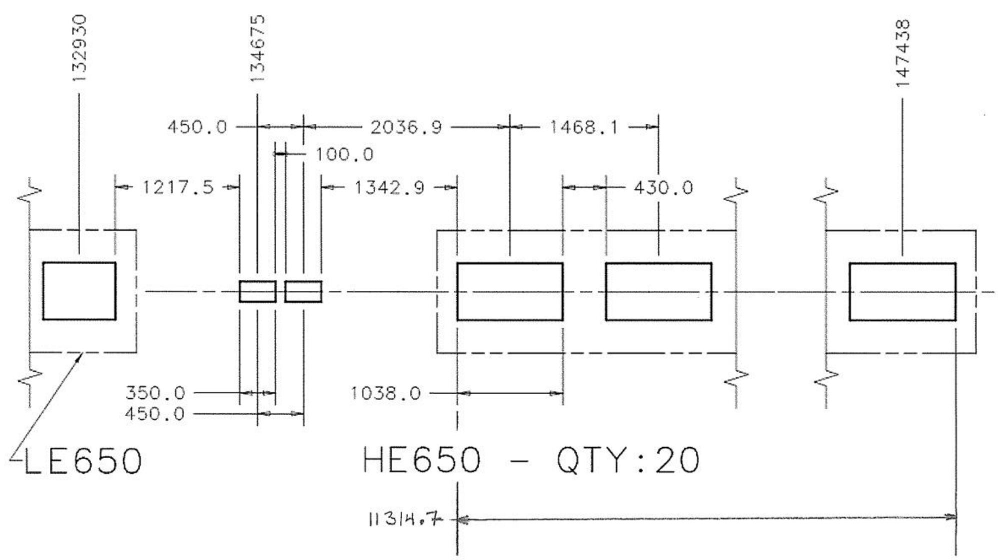

Figure 3. 650 MHz beta = 0.9 cryomodule (HE650) lattice spacing

2.4 Cryomodule vacuum design

- 2.4.1 Cryomodule end closure. The baseline cryomodule design includes separated insulating vacuum for each cryomodule. The cryomodule will be a closed, stand-alone cryomodule with connections to an external, parallel transfer line. (See Figure 2)
- 2.4.2 Each cryomodule includes at least two closed vacuum spaces: cavity/beam vacuum and cryomodule insulating vacuum. Vacuum isolation breaks separate cryomodule insulating vacuum from the transfer line vacuum.

2.5 Warm to cold transitions at the cryomodule beam tube ends

2.5.1 The baseline cryomodule structure includes short enough warm to cold transitions such that cavity to cavity spacing from one cryomodule to the next is acceptable with allowance for warm magnet(s), instrumentation between cryomodules, and access for their installation. [*We need space requirements for warm magnet, BPM, and/or other items in the warm space between cryomodules in order to divide our allocation from Figure 3 between our warm-cold transitions and these other items.*]

2.5.2 Warm-to-cold transition heat loads shall be relatively small, in particular, less than 2 Watts each to the 2 K level.

2.6 Structural stiffness

2.6.1 Aim for highest possible mechanical frequencies for mechanical vibration. *[NEED A DESIGN GOAL. For example 50 Hz for lowest mechanical mode of a cavity on its support structure.]*

2.6.2 Stresses in piping and support structures include those due to pressure loads due to the use of bellows and shall not exceed allowable stresses.

2.6.3 Piping stability with respect to loads shall also be verified

2.7 Cavity alignment requirements relative to external reference

2.7.1 Cavity lateral alignment RMS = 0.5 mm

2.7.2 Cavity vertical alignment RMS = 0.5 mm

2.7.3 Cavity positions relative to fiducials on the vacuum vessel are set during assembly with no requirement for later internal adjustment of cavity position within the cryomodule after assembly.

2.7.4 Alignment maintained (return to position within 0.5 mm RMS tolerance) with thermal and pressure cycling.

2.7.5 Final alignment is of the vacuum vessel assembly by means of the external fiducials which were referenced to the cavity string.

Table 1. Positional tolerances within the cryomodule

	Subassembly	Tolerances (RMS)	Total envelopes
Cryo-module assembly	Cavity and He vessel assembly	± 0.1 mm	Positioning of the cavity wrt. external reference ± 0.5 mm
	Supporting system assembly	± 0.2 mm	
	Vacuum vessel construction	± 0.2 mm	
	Action		
Transport, testing, and operation	Transport and handling (± 0.5 g any direction)	± 0.1 mm	Reproducibility/Stability of the cavity position wrt. external reference ± 0.3 mm
	Vacuum pumping	± 0.2 mm	
	Cool-down		
	RF tests		
	Warm-up		
	Thermal cycles		

2.8 Number of thermal cycles. The cryomodule shall be designed for a minimum of 20 thermal cycles.

2.9 Tuner. The cryomodule design shall accommodate the following tuner features.

2.9.1 Overall tuner envelope must not interfere with other features like piping

2.9.2 Tuner motor location is required to be accessible without disassembly of the cryomodule. (***Note this new requirement!***) Present baseline concept is ports on the vacuum vessel providing access to each tuner motor.

2.9.3 Tuner cabling to be routed to avoid damage

2.9.4 Cables shall be thermally intercepted at the 70 K level

2.10 RF power input coupler

2.10.1 The cryomodule includes features to accommodate the input coupler assembly including input coupler flange on the vacuum vessel and features to support any associated assembly tooling

2.10.2 Maximum allowable motion of the cold flange on the cavity relative to the warm flange on the vacuum vessel is [*need these numbers, using TTF numbers based on invar rod scheme for now*]

2.10.3 [*Will add a reference for power coupler details*]

2.11 Magnetic shielding and magnetic fields

2.11.1 Magnetic shielding is considered to be part of the dressed cavity assembly

2.11.2 No component of the cryomodule shall impose a magnetic field of more than 10 milligauss on the shielded, dressed RF cavity.

3. Cryomodule thermal and flow requirements

3.1 Temperature levels. There will be three temperature levels of helium cooling in the cryomodules.

3.1.1 RF cavity: 1.8 K to 2.1 K are possible temperatures, the precise design temperature is to be determined. This level is referred to as “2 K” in this document (including within Figure 2).

3.1.2 A next temperature level will be in the range 4.4 K to 8.0 K. A 4.4 K subcooled liquid or 2-phase system may be incorporated, or a supercritical pressure stream in the range 5.0 to 8.0 K. This level is referred to as “5 K” in this document.

3.1.3 The highest temperature level will be helium in the range 30 K to 80 K, the precise range yet to be determined. This level is referred to as “70 K” in this document.

3.1.4 There will be no liquid nitrogen in the Project X tunnel. However, for test purposes in various test cryostats and facilities, the “70 K” thermal shield may be cooled with liquid nitrogen at approximately 80 K.

3.2 Thermal shields and thermal intercepts

3.2.1 There shall be one level of radiative thermal shield at the nominally 70 K level.

3.2.2 A thermal radiation shield at the 5 K level is not required.

3.2.3 Thermal intercepts at the 5 K level shall be available for the support structure, input couplers, warm-to-cold beam tube transitions, and higher order mode (HOM) absorbers, if any.

3.2.4 The design of the nominally 5 K thermal intercepts may incorporate the use of 4.4 K 2-phase liquid helium or supercritical pressure helium. This design selection is to be made jointly with the Project X cryogenic system designers.

3.2.5 Thermal intercepts at the 70 K level shall be available for support structures, input couplers, instrument wires, tuner wires, liquid supply valve, warm-to-cold beam tube transitions, and any other components of the cryomodule for which interception of heat at a higher level than 2 K is beneficial.

3.2.6 The thermal shield shall be designed such that introduction of cold (process temperature) helium into the thermal shield piping when the thermal shield is warm, resulting in a very fast cool-down, does not damage the thermal shield or other parts of the cryomodule. (The issues are warping and associated forces, thermal stresses, etc.)

3.2.7 Thermal shield trace piping shall be arranged such that counterflow heat transfer does not inhibit cool-down of the thermal shield.

3.3 Heater for 2 K flow and pressure control

3.3.1 The presence of a steady-state pressure drop results in a pressure change at the cryomodule with a change in flow rate (e.g. due to heat load change or liquid level control valve position change), even with constant cold compressor inlet pressure (perfect cryoplant pressure regulation).

3.3.2 Heaters distributed within the cryomodules will be required to compensate for heat load changes so as to control subsequent flow and pressure changes. (See Technical Appendix for more detail.)

3.4 Evacuated multi-layer insulation (MLI) shall be used within the cryomodule

3.4.1 Vacuum vessel provides the insulating vacuum space

3.4.2 MLI shall be used on the thermal radiation shield

3.4.3 MLI shall be used on colder piping and vessels under the thermal radiation shield to reduce boiloff rates from loss of vacuum incidents

3.5 Pipe requirements

3.5.1 Heat transport from cavity to 2-phase pipe (if a closed helium vessel and 2-phase pipe are utilized): 1 Watt/sq.cm. is a conservative rule for a vertical pipe. The critical heat flux for a non-vertical pipe connection from the helium vessel to the 2-phase pipe may be considerably less than 1 Watt/sq.cm. Configurations other than vertical require analysis to verify that the anticipated heat flux is less than the critical heat flux.

3.5.2 Two phase pipe size and/or helium vessel vapor space: 5 meters/sec vapor "speed limit" over liquid and not smaller than nozzle from helium vessel

3.5.3 No downward dips or features of the 2 K vapor piping which could trap liquid as a separate bath from the main 2 K bath are permitted.

3.5.4 Gas return pipe (also serves as the support pipe in TESLA-style CM) combined with entire return vapor flow path to cold compressors: pressure drop < 10% of total pressure in normal operation

3.5.5 Loss of vacuum venting: pressure in the helium vessel of the dressed cavity less than the cold maximum allowable working pressure (MAWP) of the helium vessel and dressed cavity. Venting path includes nozzle from helium vessel, 2-phase pipe, may include gas return pipe, and also includes any external vent lines

3.5.6 Pipe shall be sized for the worst case among steady-state, peak flow rates, upset, cool-down, warm-up, and venting and conditions.

3.5.7 Total 2 K vapor volume required for pressure stability and control may be a factor influencing pipe sizes. *Volume requirements related to pressure stability are yet to be determined.*

3.6 Heat exchanger

3.6.1 A heat exchanger shall be incorporated into the cryomodule design which precools helium from approximately 4.5 K to 2.2 K upstream of the cryomodule liquid level control valve. (See figure 2.)

3.6.2 The heat exchanger may be tube-in-shell or plate-fin style.

3.6.3 The elevation of the bottom of the heat exchanger shall be at least 5 cm higher than the highest top of the 2 K liquid level in the system.

3.6.4 Shell side pressure drop shall be no more than 2 mbar at worst-case steady-state design flow.

3.6.5 Tube side pressure drop shall be no more than 100 mbar at worst-case steady-state design flow.

3.7 Cryogenic valves

3.7.1 Valves appropriate for low temperature helium cryogenic service shall be used

3.7.2 Valves shall be thermally intercepted at the 70 K level

3.7.3 Valves shall have bellows stem seals

3.7.4 Valves shall be sized and have control characteristics based on the anticipated operating flow rates with allowance for worst-case conditions such as cool-down, warm-up, or recovery from some other upset condition

3.7.5 [AD cryogenic valves may be used here]

3.8 Bayonets (or other connections to transfer line)

3.8.1 Fermilab has standard bayonet designs which are preferred for the positive pressure connections. [Will provide a reference.]

3.8.2 Jefferson Lab and SNS have a large, subatmospheric bayonet design which may be used for the subatmospheric connection to the transfer line. [*Also need a reference here.*] However, another type of connection may be used.

3.9 Maximum Allowable Working Pressures . See Table 2.

Table 2. Maximum allowable working pressures (MAWP) (differential pressure)

Region	Warm MAWP (bar)	Cold MAWP (bar)
2 K, low pressure space	2.0	4.0
2 K, positive pressure piping (separated by valves from low P space)	20.0	20.0
5 K piping	20.0	20.0
70 K piping	20.0	20.0
Insulating vacuum space	1 atm external with full vacuum inside 0.5 positive differential internal	
Cavity vacuum	2.0 bar external with full vacuum inside 0.5 positive differential internal	4.0 bar external with full vacuum inside 0.5 positive differential internal
Beam pipe vacuum outside of cavities	1 atm external with full vacuum inside 0.5 positive differential internal	1 atm external with full vacuum inside 0.5 positive differential internal

3.10 Overpressure protection

3.10.1 Helium piping and vessels shall be protected from exceeding their MAWP by means of relief valves and/or rupture disks in accordance with pressure vessel and piping standards.

3.10.1.1 Worst-case heat flux to liquid helium temperature metal surfaces with loss of vacuum to air shall be assumed to be 4.0 W/cm^2.

3.10.1.2 Worst-case heat flux to liquid helium temperature surfaces covered by at least 5 layers of multi-layer insulation (MLI) shall be assumed to be 0.6 W/cm^2.

3.10.1.3 Consideration of back pressure and flow resistance from vent discharge lines and piping downstream of the relief valves must be included in the design.

3.10.1.4 Relief valves and rupture disks for helium will be part of a vent piping system for ducting helium from the tunnel and most likely will not be mounted directly on the cryomodules.

3.10.2 The insulating vacuum is to be protected from over pressurization by means of a spring-loaded lift plate.

3.10.2.1 Worst case piping ruptures internal to the insulating vacuum shall be analyzed to determine lift plate size.

3.10.2.2 Provisions shall be provided to allow free passage of the helium out past thermal shield and MLI to the lift plate.

4. Beam tube requirements

4.1 Beam tube extensions beyond the cavities, such as at cryomodule ends, are to be “particle free” and cleaned for UHV like the cavities themselves.

4.2 Attachments to the beam tube, such as vacuum valves and beam position monitors are to be clean and “particle free”, which means wet-washed, not just blown clean with gas.

4.3 Cold-to-warm transitions shall include 5 K and 70 K thermal intercepts.

4.4 Attention may be required for RF characteristics of bellows and any beam pipe cross-section changes or asymmetries [*check on this*]

5. Instrumentation

5.1 RF
- 5.1.1 Cavity field probe
- 5.1.2 Coupler e-probes
- 5.1.3 Diode x-ray detectors

5.2 Tuner diagnostics

5.3 Temperature sensors
- 5.3.1 Input couplers
- 5.3.2 Thermal shields
- 5.3.3 Cavity helium vessel

5.4 Pressure sensors
- 5.4.1 Helium bath pressure in the nominally 30 mbar system

5.5 Helium bath liquid level for the nominally 30 mbar, 2 K system

5.6 Heaters in the 2 Kelvin region for liquid level and pressure control.

5.7 Position monitors

5.8 Cavity vacuum, insulating vacuum, and input coupler vacuum gauges

5.9 Beam position monitors (any cold ones?)

5.10 Vibrations sensors

5.11 Wires shall be of a material and/or thickness to minimize heat input to the low temperature levels.

6. Cryomodule test requirements.

6. Cryomodule test requirements. The cryomodule will be tested before installation in the linac. Tests will check the following:

6.1 Leak and pressure tests for quality assurance and FESHM compliance.

6.2 Temperature profiles

6.3 Approximate heat loads

6.4 RF cavity performance

6.5 Tuner performance

7. Project interfaces

7.1 Cavity[2]. The cryomodule project shall interface to the cavity at the cavity end flanges, cavity support points, the RF input and output, and instrumentation feedthroughs.

7.2 Magnets. The cryomodule project interface to the magnets occurs at the warm beam tube flange just outside of the cryomodule vacuum end cover.

7.3 RF interfaces occur at the power input couplers and RF instrumentation connectors on the vacuum shell.

7.4 Cryogenic system. The interfaces to the cryogenic system occur at bayonets, relief vent piping, cool-down line piping, and instrumentation connectors.

7.5 Instrumentation

8. Engineering and safety standards

All designs shall be built to applicable FNAL engineering and safety standards.

9. Quality assurance requirements

A complete cryomodule traveler is to be developed documenting all stages of materials inspection, cryomodule component fabrication, piping and weld inspection, cryomodule assembly, and test.

10. Reviews

All the designs will undergo reviews at the appropriate stages of design, for example conceptual, engineering, and procurement readiness reviews. Appropriate review committees consisting of experts will be convened by the Project X/SRF management team.

11. **Technical Appendix.** Some additional analyses and experience are included in this section as guidance for the cryomodule design.

11.1 Guidance for thermal analysis. S1-Global cryomodule heat load measurements [6, 7] have provided some very informative recent measurements for cryomodules of this type.

11.1.1 Thermal radiation to the 2 K or 5 K level under an 84 K thermal shield: 0.045 W/m2

11.1.2 Thermal radiation to 80 K thermal shield from room temperature vacuum vessel: 1.62 W/m2

11.2 Estimated heat loads for initial design [8, 9]

Heat loads will depend on the detailed cryomodule design. However, for initial design purposes the following heat loads (Table 3) at each temperature level should be used. These are the best estimate of heat load multiplied by a factor 1.5 for pipe sizing. RF cavity dynamic loads come from reference 6. Heat loads for current leads, input couplers and various static heat loads are added to those RF dynamic loads to get the totals in reference 7, shown in Table 3.

Table 3. Heat loads for pipe sizing [9]

2 K heat load basis for pipe size*	
per cavity (W)	38.75
per cryomodule (W)	311.77
5 K heat load basis for pipe size*	
per cryomodule (W)	50.48
70 K heat load basis for pipe size*	
per cryomodule (W)	653.46

*Heat loads for pipe sizing include uncertainty/design factor 1.5

11.3 Pressure stability with 2 K heat load and flow rate changes. For a 650 MHz cryomodule with the mass flow due to predicted 2 K heat and nominal design pressure drop through the return line, a 2.5% flow rate change provides a 0.1 mbar pressure change at the cryomodule, our desired limit. (See Table 4.) Thus, heater control will need to be on the order of 1Watt and size on the order of 200 W if we are to compensate for RF turned off.

Table 4. Flow change which results in a 0.1 mbar pressure change at the CM

	2 K predicted heat (W)	2 K helium mass flow (g/sec)	JT HX pressure drop (mbar)	Allowed pressure change (mbar)	Corresponding flow change (g/sec)	Corresponding heat load change (W)	%change flow
650 MHz beta = 0.9 CM	**207.85**	**11.11**	**2.00**	**0.10**	**0.27**	**5.13**	**2.47%**

11.4 Pipe sizes. Our heat load estimates, arrangement of 8 cavities into strings with stand-alone cryomodules, and emergency venting scenarios imply helium flow requirements which can be translated to pipe sizes. The following information is not final and should not be considered as “requirements”, but it provides guidance and derives from current understanding of requirements.

11.4.1 Figure 4 (from reference 8) shows the number of RF cavities in a series, with 38.75 W at 2.0 K per cavity (see Table 2), which result in a peak vapor velocity of 5 meters/sec, our vapor “speed limit” for saturated vapor over liquid (section 3.6.2). Based on operational experience for the FLASH linac at DESY where liquid levels in the 2-phase pipe are about 40 mm +/- 10 mm, I assume here a 50 mm liquid level in the pipe. The space for vapor flow, then, excludes the cross-sectional area of pipe occupied by liquid helium. This plot illustrates the minimum 2-phase pipe diameter, including allowance for the cross-sectional area occupied by liquid, for the string of cavities. The result for a cryomodule consisting of 8 cavities with flow out the end of the cryomodule is about 10 cm ID. The pipe could be smaller with flow out of the cryomodule at some intermediate location, but as is shown in 13.2, emergency venting sets the pipe size.

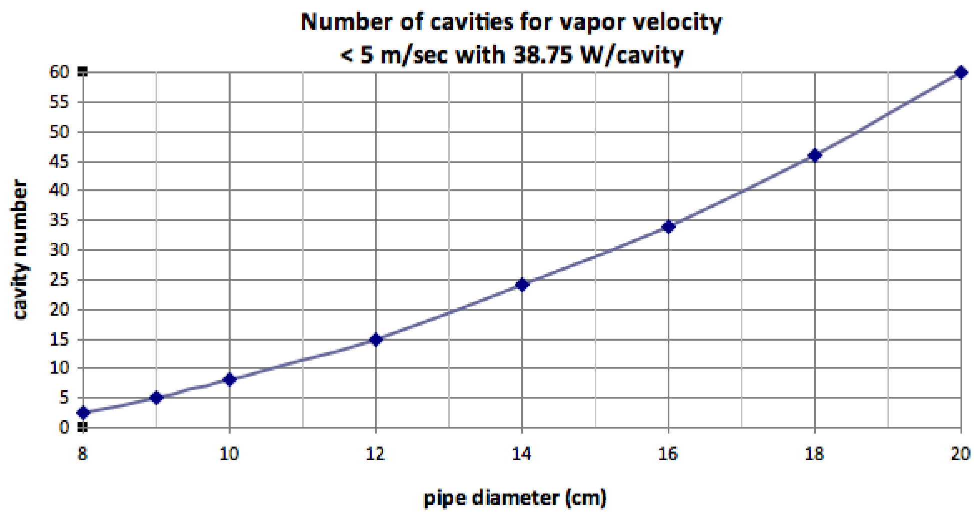

Figure 4. Number of 650 MHz cavities in series, using 1.5 x estimated heat load, which result in a vapor flow rate of 5 meters/sec versus pipe size.

11.4.2 Figure 5 (from reference 9) shows pressure drop through the 2-phase pipe with 650 MHz RF cavities venting due to loss of cavity vacuum. One can see that for 8 cavities in series, a 5-inch pipe is becoming marginally small. Given the uncertainties in these analyses and the need for a pressure drop in other parts of the system including vent piping, I recommend 6-inch pipe, hence the 16.15 cm number in the Table in 13.3.

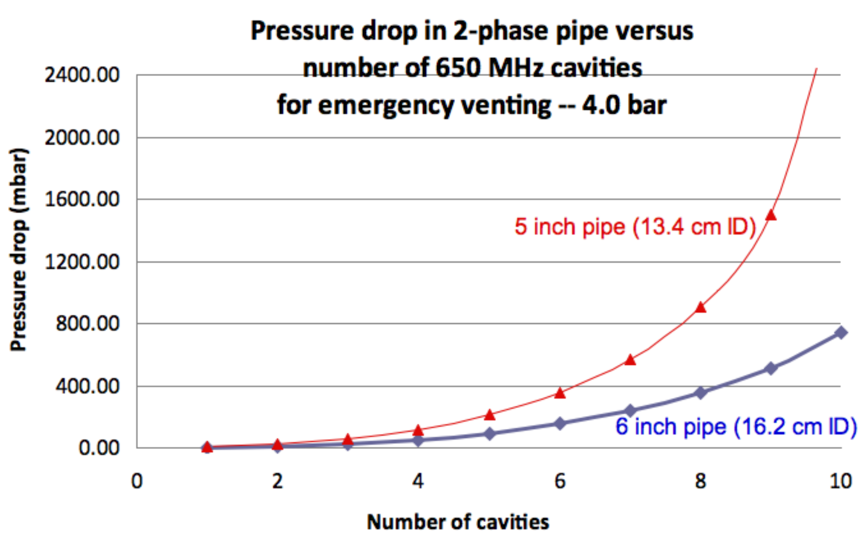

Figure 5. Loss of cavity vacuum to air -- venting pressure drop in 2-phase pipe

11.4.3 Table 5 (from reference 7) summarizes steady-state pipe sizing analyses for all Project X cryomodules along with emergency venting results for just SSR1 and 650 MHz, beta = 0.9, cryomodules. Conclusions are highlighted in blue. In particular, for 650 MHz, beta

= 0.9, 8 cavities per cryomodule, the 2-phase pipe size is determined by emergency venting requirements to be at least 162 mm ID.

Table 5. Pipe sizes based on present heat load estimates for stand-alone cryomodules, steady-state flow, and emergency venting flow [9,10,11]

Pipe sizes for stand-alone cryomodules					
	based on steady-state cooling requirements				
	325 MHz SSR0	325 MHz SSR1	325 MHz SSR2	650 MHz beta = 0.61	650 MHz beta = 0.9
2 K heat load basis for pipe size*					
per cavity (W)	5.35	5.89	7.86	37.70	38.75
per cryomodule (W)	46.66	54.11	83.30	234.59	311.77
2 K connection to helium vessel, ID (cm)	3.39	3.56	4.11	9.01	**9.13**
2-phase helium pipe (5 cm liquid), ID (cm)	7.24	7.35	7.80	9.50	10.20
5 K heat load basis for pipe size*					
per cryomodule (W)	439.41	154.07	123.81	66.41	50.48
5 K - 8 K thermal shield pipe ID (cm)	1.57	1.57	1.57	1.57	1.57
70 K heat load basis for pipe size*					
per cryomodule (W)	2059.16	729.95	690.03	662.16	653.46
70 K thermal shield pipe ID (cm)	2.50	2.50	2.50	2.50	2.50
*Heat loads for pipe sizing include uncertainty/design factor 1.5					
	based on emergency venting requirements				
2 K connection to helium vessel, ID (cm)		**4.50**			5.90
2-phase helium pipe, ID (cm)		**12.30**			**16.15**

11.4.4 Thermal shield pipe sizes shown in Table 5 are small since total heat loads and required flow rates are small for these short (compared to TESLA, for example) strings of cavities. Steady-state pressure drops in the 650 MHz cryomodule for the pipe sizes shown are around 10 mbar or less. [*Pipe sizes shown should be checked for cool-down, warm-up, and for heat transfer through the pipe wall to the helium.*]

12. Acknowledgements

[If you help edit this and/or provide information, I like what you say, and you do not wish to remain anonymous, I will put your name here.]
Thanks for editorial and technical input:
Tom Nicol, Arkadiy Klebaner, Camille Ginsburg, Prashant Khare

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[7] "S1-G Cryomodule Thermal Performance Summary" in the file: "S1-G Cryomodule Thermal Performance Summary(ALPCG11).pdf" by Norihito Ohuchi, presented at the ALPCG11 meeting on March 22, 2011. File available at http://ilcagenda.linearcollider.org/contributionDisplay.py?contribId=238&confId=4572
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[11] Emergency venting flow rate and pipe size estimates from "CryomoduleVentingCalcs-29Dec2010.xls", Tom Peterson, revision March 29, 2011
[12] [*More to be added*]